

Evaluation of the Harmful Algal Bloom Mapping System (HABMapS) and Bulletin

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Executive Summary

This report describes the National Oceanic and Atmospheric Administration (NOAA) Harmful Algal Bloom (HAB) Bulletin and Mapping System and discusses the potential of NASA remote sensing data and modeling products for enhancing this decision support tool. The NOAA HAB Mapping System and Bulletin provide a Web-based GIS mapping system and an e-mail alert system that allow the detection, monitoring, and tracking of HABs in the Gulf of Mexico. The HAB Mapping System consists of GIS data layers developed by its parent, overarching program, HABSOS. The key inputs to HABMapS are cell counts, buoy and satellite winds, atmospheric model forecasts, surface currents, SST, bathymetry, county maps, major rivers, cities, shellfish beds, and marine and estuarine reserves. The HAB Bulletin alerts users of a HAB in the Gulf of Mexico, and HABMapS begins to monitor, map, and forecast the trajectory and dynamics of the bloom. These Bulletins represent a collaborative effort among NOAA CoastWatch, the National Ocean Service Center for Coastal Monitoring and Assessment, and NOAA Coastal Services Center that began as a demonstration project in 1999 and will become operational in September 2004.

NASA Earth Science data that potentially support HABMapS/Bulletin requirements include ocean color, sea surface temperature (SST), salinity, wind fields, precipitation, water surface elevation, and ocean currents. Modeling contributions include ocean circulation, wave/currents, along-shore current regimes, and chlorophyll modeling (coupled to imagery). The most immediately useful NASA contributions appear to be the 1-km Moderate Resolution Imaging Spectrometer (MODIS) chlorophyll and SST products and the (presently used) SeaWinds wind vector data. MODIS pigment concentration and SST data are sufficiently mature to replace imagery currently used in NOAA HAB applications. The large file size of MODIS data is an impediment to NOAA use and modified processing schemes would aid in NOAA adoption of these products for operational HAB forecasting. Other relevant areas where NASA contributions could be important are atmospheric/ocean circulation modeling and their coupling, as well as sea surface height data. NOAA HAB models rely on accurate hydrodynamic and meteorological information model input for prediction of HAB location and trajectory (especially when clouds obscure satellite imagery) and what the bloom population dynamics might be at that specific place and time. Enhanced model development is the single most important development area that could aid NOAA HAB forecasting. The baseline model performance is the present non-automated, heuristic approach with several model outputs used by NOAA scientists to make intelligent determinations for HAB forecasting. With more accurate model development, computer simulations could improve forecasts with less cost and time expenditure.

1.0 Introduction

To improve life here,

To extend life to there,

To find life beyond.

This is the NASA vision. This vision, in turn, has shaped NASA's mission:

To understand and protect our home planet,

To explore the universe and search for life,

To inspire the next generation of explorers...as only NASA can.

The NASA vision and mission statements include a clear focus on the Earth and on life on Earth. NASA's Earth Science Enterprise (ESE) is the primary manifestation of NASA's mission in Earth science and applications. Dr. Ghassem R. Asrar, NASA's Associate Administrator for Earth Science, has stated that, *"NASA develops unique capabilities for exploration of the universe and space, and we focus them on our planet Earth. We make readily available the information and knowledge we generate so it can be used for understanding and protecting our planet to enhance the quality of life for present and future generations"* (NASA, 2004).

As part of a systematic approach to extending the benefits of NASA's Earth science to the broader community, the Earth Science Enterprise has identified 12 applications of national priority. These 12 national applications have been determined using criteria including the consideration of potential socio-economic return, application feasibility, and appropriateness for NASA, and partnership opportunities (Figure 1). The Applications Division of the ESE, in partnership with public and private organizations, employs a systems engineering process to integrate and benchmark NASA inputs into operational decision support systems across these 12 application areas. This report is an element of the Coastal Management national application.

1.1 NASA's Coastal Management Program

The goal of NASA's Earth Science Applications Coastal Management Program is to enable partners' beneficial use of Earth science, observations, models, and technology to enhance decision support capabilities serving their coastal management and policy responsibilities. The major tenets of the Coastal Management Program are as follows:

- Develop and nurture partnerships with appropriate coastal organizations.
- Identify and assess partners' coastal management responsibilities, plans, and decision support tools and evaluate the capacity of Earth science results to support the partners.
- Verify and validate the application of Earth science results with partners, including development of products and prototypes to meet partners' requirements.

- With partners, document the value of Earth science results relative to the benchmark capability of the partners' decision support tools and support their adoption into operational use.
- Communicate results and partners' achievements to appropriate coastal communities and stakeholders.

Coastal resources compose a crucial component of American society, and the coastal regions play a fundamental role in the national and global economy. Observations from airborne and spaceborne platforms have been used for decades to map the world's oceans and coasts. Such imagery has been the basis for decisions that affect coastal resource management and policies. The National Oceanic and Atmospheric Administration (NOAA) collaborates with NASA to evaluate NASA technology for integration within NOAA operational decision-making processes.

Providing coastal-resource-related guidance is one of NOAA's many responsibilities. The National Center for Coastal Ocean Science (NCCOS) provides harmful algal bloom (HAB) related information for NOAA. This report evaluates the potential for NASA to enhance the NOAA Harmful Algal Bloom Mapping System (HABMapS) and associated HAB Bulletin with NASA Earth science inputs.



Figure 1. NASA Earth Science Enterprise applications of national priority.

1.2 Harmful Algal Bloom (HAB) Overview

Congress passed the Harmful Algal Bloom and Hypoxia Research and Control Act in 1998 (P.L.105-383). This Act called for the establishment of an interagency task force to study HABs and hypoxia, and for an assessment of these problems both nationally and especially for the Gulf of Mexico (GOM). HABs in the GOM are a regional problem, i.e., several states may mitigate the effects of one bloom event (Stumpf et al., 2003).

Some researchers link the increase in HAB frequency and severity to an increase in human occupancy of the coast; population growth produces a corresponding increase in nutrient effluent to local waters. The sources of these nutrients are farm and home fertilizers, farm animal waste, and human waste funneled into tributaries and streams. Over the last two decades, an estimated \$1B of worldwide damage has been due to the occurrence of HABs (GEOHAB, 1998).

Approximately half of the 100 known toxic algal species occur in the Gulf of Mexico. Even at low concentrations, toxins from these species can adversely affect coastal resources and public health (Anderson, 1995). The most troublesome and common harmful algal species in the Gulf of Mexico is *Karenia brevis* (*K. brevis*), formerly known as *Gymnodinium breve* (average cell diameter of 30 μm). *K. brevis* is responsible for the so-called “red tides” that normally occur along the western part of the Florida shelf. *K. brevis* blooms that affect the west Florida coast often appear in late July or August, a period when other algal groups are less likely to bloom (Tester and Steidinger, 1997). Several hypotheses exist on the mechanisms of HAB initiation within the northern Gulf of Mexico. The Gulf of Mexico Loop Current is a proposed carrier of *K. brevis* seed populations within the Florida Shelf. Due to local upwelling fronts, this intrusion of the Loop Current onto the West Florida shelf (Figure 2) would aid the onshore transport of a HAB. Saharan dust carried by high-level winds across the Atlantic is another suggested cause of HAB initiation (Penta et al., 2001) (Figure 3). These iron-rich particles settle in the GOM and can initiate blooms of cyanobacteria (*Trichodesmium erythraeum*) which use iron to fix nitrogen gas. Having this fixed nitrogen in a soluble form which can be utilized by phytoplankton produces environmental conditions favorable for phytoplankton growth and, subsequently, favorable for bloom initiation.

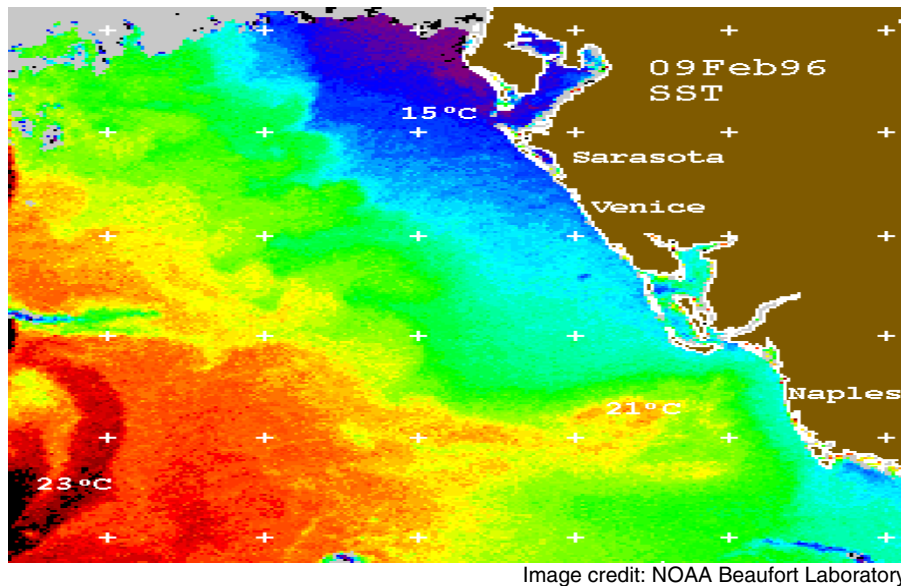
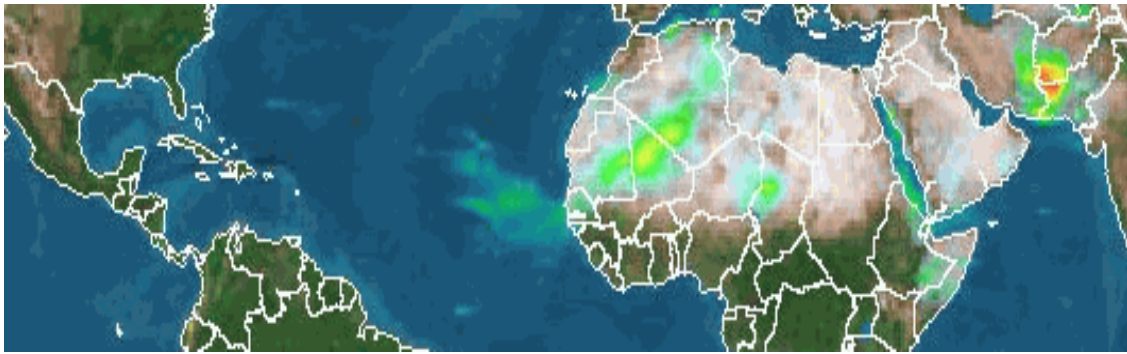


Image credit: NOAA Beaufort Laboratory

Figure 2. Loop Current impinging on the West Florida Shelf.



Credit: NASA

Figure 3. Transoceanic transport of Saharan, iron-rich dust.

One important ecological constraint on bloom development and evolution is water clarity; areas affected by sediment plumes and dissolved material, e.g., Louisiana and certain parts of Florida, have low occurrences of HABs due to the decreased water clarity in these areas (Tester and Steidinger, 1997). Another constraint on bloom development is salinity; *K. brevis* does not usually bloom in waters with salinities greater than 30 psu (Tester et al., 1998).

K. brevis cell counts of 5000 l⁻¹ are sufficient to close shellfish beds. HAB toxins can affect coastal economies, fisheries, and public health. Consumption of HAB-affected seafood may cause a variety of human illnesses; *K. brevis* contains brevetoxin, a potent neurotoxin. Furthermore, when a HAB is active offshore, it is possible that windblown spume, which carries suspended HAB particles, can initiate asthma-like attacks in coastal populations. Globally, contaminated shellfish consumption accounts for approximately 2000 reported instances per year of human poisoning; fifteen percent of these cases are fatal (GEOHAB, 1998).

A potential consequence of any algal bloom may be temporary hypoxia. Seasonal, thermal stratification of the water column creates sharp density gradients and prevents effective vertical mixing. During summer months, the spring phytoplankton bloom sinks, and decomposition of organic matter is confined to bottom waters, which are soon depleted of oxygen by heterotrophic activity. Seasonal hypoxia occurs in the Gulf of Mexico and usually affects productive fisheries areas. Gulf of Mexico tourist areas affected by HAB events are often sites of seasonal hypoxia.

2.0 HABSOS and HABMapS

Following a requirements workshop for the Global Ocean Observing System (GOOS), the Harmful Algal Blooms Observing System (HABSOS) was conceived at a HABs forecasting workshop in 1997 and launched in 2000 (Stumpf et al., 2003). HABSOS subsumes HABMapS as part of its programmatic structure. HABSOS, originally conceived as a proof-of-concept infrastructure for discovery, tracking, prediction, and mitigation of HABs, was to develop into an open, Web-based, user-driven, onset-to-demise HAB data communication and management system for the GOM. The HABSOS effort is a partnership involving several federal, state, and local agencies, as well as academic marine research laboratories. The major stakeholders of this effort are NOAA, the U.S. Environmental Protection Agency, the U.S. Navy, and state agencies in Alabama, Mississippi, Louisiana, Texas, and Florida.

HABMapS combines a Web front-end interactive map with a geographic information system (GIS) that collects, stores, and displays various data layers for target user groups (Figure 4). The target user groups

of HABMapS are Federal, state, and local resource and environmental managers and scientists. The primary data layers of HABMapS are satellite products and buoy observations (Table 1) supplemented, when available, by *in situ* counts of HAB organisms. Image data are interlinked and ingested into the HABMapS GIS. One component of this GIS is a Web-based interactive display tool. This tool provides a visual display of the data in a useable form for researchers, government policy makers, and resource managers.

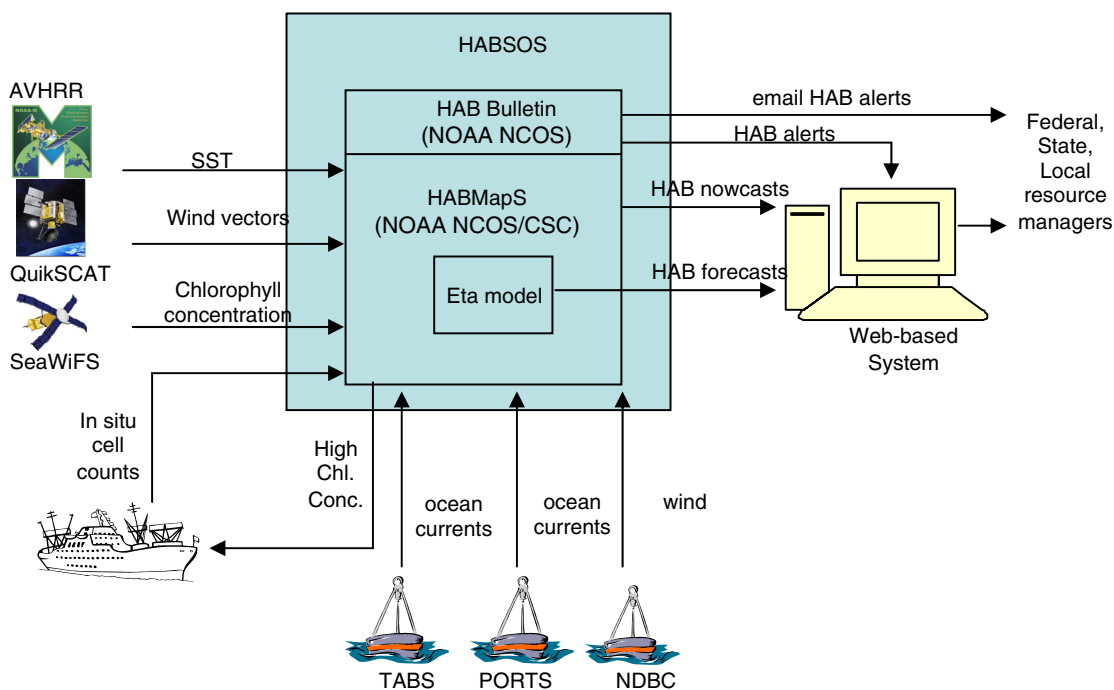


Figure 4. Flowchart of data input and products in HABMapS.

Although NOAA uses a variety of heuristic models to improve prediction capability from satellite and *in situ* data, atmospheric models providing near-term meteorological forecasts are the most useful to their HAB forecasting and nowcasting efforts (Stumpf, 2004). NOAA scientists currently use the Eta¹ model, refined at the National Center for Environmental Prediction (NCEP), to forecast HAB movements several days in advance (Stumpf, personal communication). Eta is a limited-area grid-point model with a comprehensive physics package (Janjic, 1990; 1994). This efficient and robust model is suitable for short-range forecasting and is operational within the weather centers of several countries.

A variety of participating networks or groups, including the Texas Coastal Ocean Observation Network (TCOON), the Texas Automated Buoy System (TABS), the National Data Buoy Center (NDBC), the Coastal Ocean Monitoring and Prediction System (COMPS), the Sustained Ecological Research Reserves (NERRS), and the Gulf of Mexico Coastal Ocean Observing System (GCOOS), provide data and modeling capabilities for ingestion within HABMapS. TABS, initially established for oil spill response, collects ocean surface current vector data and ingests it into a GIS hosted at Texas A&M University. Users can gain access to current and archived TABS data, at no cost, via a Web-based interactive map portal (<http://tabs.gerg.tamu.edu/>).

¹ The Eta model gets its name from the vertical coordinate η , originally defined in Mesinger (1984).

average by more than 0.6 mg m^{-3} is flagged as a potential HAB. Ship-based reconnaissance is then used to determine the nature of the algal population (HAB or non-HAB) and to validate satellite-predicted chlorophyll concentrations with in-situ measurements. AVHRR data provides SST maps of GOM waters. Wind vectors from QuikSCAT may be used with SST imagery to track weather, ocean currents, and possible fronts, although no satellite-derived wind vectors are currently used for HAB trajectory analyses.

HAB mitigation requires accurate monitoring of HAB-affected areas and communication between responsible agencies and the public. Advance notice of a HAB event increases the options for monitoring and harvesting shellfish and for beach cleanup. In an effort to provide stakeholders with up-to-date information, the NOAA Coastal Services Center (CSC) e-mails HAB Bulletins to subscribers in near-real time when a HAB exists in the GOM. These bulletins provide information on HAB trajectories, environmental conditions surrounding a HAB, conditions that are suitable for a new bloom to form, meteorological data (e.g., wind speed and direction), and chlorophyll maps derived from SeaWiFS (Figure 6). NOAA provides the HAB Bulletin only to registered users because of commercial licensing issues associated with the SeaWiFS imagery. These Bulletins represent a collaborative effort among NOAA CoastWatch, the NOS Center for Coastal Monitoring and Assessment, and NOAA CSC that began as a demonstration project in 1999 and will become operational in September 2004.

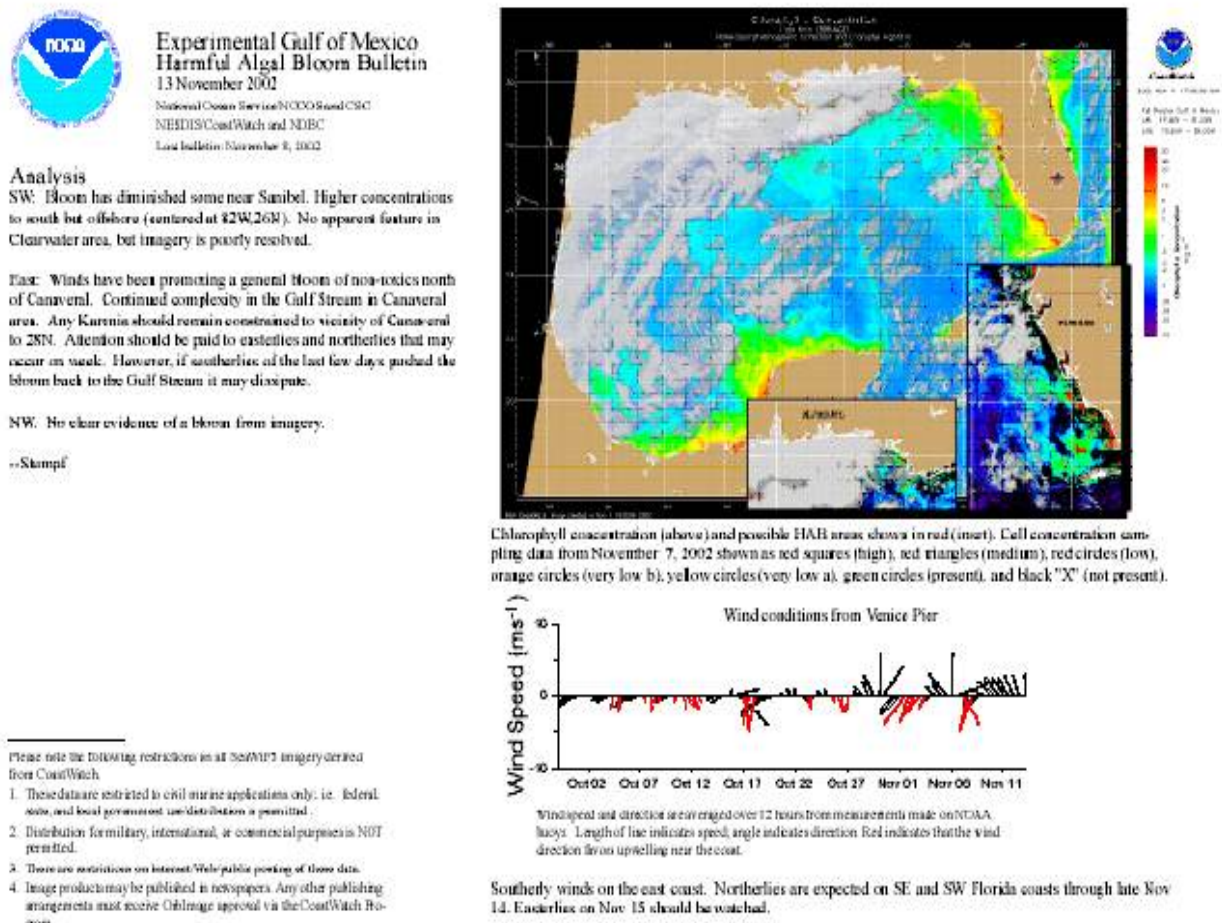


Figure 6. Experimental NOAA HAB Bulletin. An analysis of the bloom severity and weather conditions is given in the upper left, a SeaWiFS image of chlorophyll concentration is shown in the upper right, and local wind vectors are shown over time in the lower right. Archived HAB Bulletins are available on the NOAA CoastWatch website (http://coastwatch.noaa.gov/hab/bulletins_ns.htm).

3.0 Consideration of NASA Inputs

The types of NASA data that potentially support HABMapS/Bulletin requirements include ocean color, SST, salinity, wind fields, precipitation, water surface elevation, and ocean currents. Modeling contributions include ocean circulation, wave/currents, along-shore current regimes, and chlorophyll modeling (coupled to imagery).

3.1 Overview of Current and Planned NASA Inputs

Table 2. DST requirement and potential NASA input match.

DST Observation Needed	DST Requirements	NASA Capability	Comments
Ocean Color (Chlorophyll)	Spectral band coverage: 400–900 nm for ocean color extraction Spatial resolution: 1 km Revisit time: 1-2 days Dynamic range: at least 10 bits SNR: sufficient over water scenes	<u>SeaWiFS</u> Level 2 and Level 3 ocean color products: Meet HABMapS requirements <u>MODIS</u> Chlorophyll pigment product: effectively meets HABMapS/Bulletin spectral and SNR requirements Spatial resolution: 1 km <u>UNMET:</u> The process to product needs to be adapted to NOAA's use <u>UNCERTAIN:</u> Accuracy of product for coastal regions; needs evaluation for HABMapS needs	<u>MODIS</u> Chlorophyll product can supplant SeaWiFS data currently used in HABMapS/Bulletin
Sea Surface Temperature	Spectral coverage: 3–14 μm Spatial resolution: ~1 km Revisit time: 1-2 days	<u>AVHRR</u> SST data products: Meet present HABMapS requirements <u>MODIS</u> SST products: Potentially meet HABMapS requirement Spatial resolution: 1 km <u>UNMET:</u> Temperature product needs to be adapted to NOAA's use <u>UNCERTAIN:</u> Accuracy of SST product for HABMapS use has not been evaluated	<u>MODIS</u> SST product appears able to supplant the AVHRR data product presently relied on by HABMapS

Table 2. DST requirement and potential NASA input match. (continued)

DST Observation Needed	DST Requirements	NASA Capability	Comments
Wind Speed and Direction	<ul style="list-style-type: none"> • Revisit time: 1-2 days • Spatial resolution: 10–30 km • Accuracy: 1-2 m/s in wind velocity 	SeaWinds on <u>QuikSCAT</u> Meets HABMapS requirement: for at least a daily wind speed and direction measurement; available at 25-km spatial resolution; wind speed and direction accuracy of 2 m/s and 20°	<u>QuikSCAT</u> Data is already in use by HABMapS
Wind Speed and Direction (continued)	<ul style="list-style-type: none"> • Revisit time: 1-2 days • Spatial resolution: 10–30 km • Accuracy: 1-2 m/s in wind velocity 	<u>AMSR-E</u> Potentially meets HABMapS requirement: for at least a daily wind speed and direction measurement; available at 25-km spatial resolution; wind speed and direction accuracy of 2 m/s and 20° <u>UNMET</u> : Product needs to be adapted to NOAA's use; question concerning repeat cycle of 1-2 days <u>UNCERTAIN</u> : Accuracy of product for HABMapS use has not been evaluated	Potential source of satellite-derived sea wind vector data
Ocean Surface Topography/ Ocean Circulation	<ul style="list-style-type: none"> • Vertical accuracy: 4-5 cm • Repeat cycle: 10–14 days 	<u>Jason-1</u> <u>NO REQUIREMENT</u> but may be useful for input to hydrodynamic models for HAB trajectory forecasts	This dataset is potentially useful for conjecturing the motion of an identified HAB
Future Sea Surface Salinity	<ul style="list-style-type: none"> • Repeat cycle: 714 days • Salinity accuracy: 0.2 psu 	<u>Aquarius</u> (planned) <u>NO REQUIREMENT</u> but data may be useful as input to hydrodynamic models for forecasting; useful for research in HAB dynamics	Modeling the development of HAB conditions, evolution, and demise of a bloom may involve local salinity gradients

Table 2. DST requirement and potential NASA input match. (continued)

DST Observation Needed	DST Requirements	NASA Capability	Comments
Future Ocean Color/SST	<u>Ocean Color</u> <ul style="list-style-type: none"> • Spectral band coverage: 400–900 nm for ocean color extraction • Spatial resolution: 1 km • Revisit time: 1-2 days • At least 10-bit dynamic range • Sufficient SNR over water scenes <u>SST</u> <ul style="list-style-type: none"> • Spectral coverage: 3–14 μm • Spatial resolution: ~1 km • Revisit time: 1-2 days 	<u>VIIRS</u> Planned SST and ocean color products will potentially meet HABMapS requirements because of higher spatial resolution (0.65 km)	This future mission will provide continuity of data for HAB-related imagery
Precipitation	<ul style="list-style-type: none"> • Spatial resolution: 1–10 km • Repeat cycle: 2060 days 	<u>TRMM</u> Potentially meets HABMapS requirement: <ul style="list-style-type: none"> • Spatial resolution: 1–5 km • Repeat cycle: 25–50 days <u>UNMET: Product needs to be adapted to NOAA's use; question concerning repeat cycle of 1-2 days; useful for input HAB ecological dynamics</u>	Potential use for modeling HAB dynamics because a decrease in salinity has a negative effect on HAB strength

3.1.1 Ocean Color

NOAA produces CoastWatch MODIS ocean color products in near-real time from global data collected by the NASA Goddard Space Flight Center (GSFC). These products are provisional and currently provided by NOAA on a "best effort" basis. NOAA obtains Level-0 data from NASA GSFC in 5-minute granules. These Level-0 datasets are processed to geolocated, calibrated radiances (Level 1b) and derived MODIS data products (Level 2) using modified versions of NASA MODIS Adaptive Processing System (MODAPS) software. These products are then mapped to the CoastWatch geographic regions.

CoastWatch MODIS ocean color products currently are limited to chlorophyll-a concentration (SeaWiFS analog - OC3M) and sea-surface temperature (Daytime 11-12 micron skin temperature). These products are available online in HDF, PNG, GeoTIFF, and Binary Raster. The color scaling for the chlorophyll-a values is identical to the scaling used in the NOAA CoastWatch SeaWiFS chlorophyll-a product. Products generated by NOAA are of operational quality and will likely differ from the same product

generated by NASA. Due to the constraint imposed on near-real time generation, NOAA uses ancillary data, predicted ephemerides, and predicted calibration tables. These ancillary data are different from those used to generate NASA science products but the resulting operational products show good agreement with respect to patterns and gradients.

Currently, species identification by SeaWiFS is not possible. Tester *et al.* (1998) estimated that about 10^5 cells l^{-1} were necessary for remote detection of *K. brevis* based on retrospective analysis of NASA's Coastal Zone Color Scanner data, a level that may give early warning of fish kills, but not shellfish toxicity. The ability to detect harmful species remotely is limited to situations where the surface signal from the HAB species is much greater than the 'noise' from co-occurring species and other non-biogenic materials in coastal waters (Tester et al., 1998). However, once verified by in-situ sampling, SeaWiFS imagery can detect *K. brevis* concentrations of 50,000 cells l^{-1} or more (Tester et al., 1998), provided background chlorophyll concentrations are 0.5 mg m^{-3} or less. Since shellfish beds must close when the *K. brevis* concentration exceeds 5000 cells l^{-1} , remote sensing alone is not able to determine when to close shellfish harvesting. However, the use of remote sensing to identify HABs may reduce occurrences of human respiratory illness and fish kills, impacts that occur at *K. brevis* concentrations exceeding 100,000 cells l^{-1} . Climatological methodology has increased the sensitivity of SeaWiFS imagery to HAB blooms (Stumpf, 2001). This method aids in the detection of new blooms and in the mapping and forecasting of bloom trajectories. The approach detects an anomaly when there is a difference between the chlorophyll concentration in a current scene and a mean chlorophyll concentration of the last three months. The running mean terminates two weeks before the current imagery; the additional two weeks act as a buffer for noise in the current chlorophyll scene.

MODIS is a NASA asset on both the Aqua and Terra platforms and represents a planned ocean-color data source for HABSOS/HABMapS. MODIS has nine bands that are useful for ocean color imagery and relevant bands used for atmospheric correction. MODIS also possesses thermal channels used for SST prediction. The spatial resolution of these relevant channels is 1 km – the same spatial resolution as SeaWiFS – and the swath width of the imagery is 2330 km cross track. Presently, NOAA NCCOS is examining using MODIS; however, the size of the data stream itself makes it difficult to work with (Stumpf, 2004). A chlorophyll MODIS data product (MOD_chlor2) is available that would parallel the presently used HABMapS SeaWiFS-based chlorophyll product. MODIS chlorophyll estimates are produced daily at Level 2 and produced daily, 8-day weekly, monthly, and yearly at Level 3. Valid data exist only for ocean cloud-free pixels, and the weekly composite is an average of cloud-free acquisitions for each ocean pixel. The MODIS chlorophyll concentration product is sufficiently mature to replace the SeaWiFS imagery currently used in the HABMapS display and in the HAB Bulletin. Since SeaWiFS has been operational since 1997 and has a planned lifetime of seven years, MODIS provides data continuity for the HAB tracking activities.

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) is a planned future platform (launch year 2008) that will carry an ocean color sensor. The NPOESS Preparatory Project (NPP) is a joint NASA/NOAA sensor risk-reduction effort that will serve as a transition between the NASA EOS program and NPOESS. NPP will supply SST and ocean color data, as well as aerosol data needed for atmospheric correction. The prospective launch date for NPP is 2006. Onboard both NPOESS and NPP, the Visible/Infrared Imager/Radiometer Suite (VIIRS) sensor will collect data in seven visible channels with a channel-to-channel variability ranging from 15 nm to 39 nm spectral width and some thermal channels which may be used for SST.

3.1.2 Sea Surface Temperature

SST is a valued input to predictions of HAB trajectories. NOAA currently uses SST data from AVHRR to map ocean transport features responsible for HAB movement (Keafer and Anderson 1993). NOAA CoastWatch provides AVHRR SST images four times daily for the U.S. coast and has an automated processing system for these data.

NOAA has a variety of satellite platforms from which to disseminate SST data to its line offices. Geostationary Operational Environment Satellites (GOES) can provide 4-km SST data every hour. Because clouds inhibit SST collection, availability of radar altimeter data during cloudy periods could aid in determining where relevant ocean features are located. NOAA CoastWatch Central Operations provides SST products derived from GOES in near real-time and updated every 3 hours. NOAA NESDIS Information Processing Division processes data from NOAA Polar Operational Environmental Satellites (POES) to provide SST imagery to CoastWatch. NOAA CoastWatch provides near real-time MODIS SST products from the NASA Terra and Aqua spacecrafts. Currently, only daytime imagery is supported within 24 hours of observation. NOAA CoastWatch is planning to provide near real-time TMI SST products from the NASA TRMM spacecraft. Currently, ascending and descending passes are available as a global dataset within 24 hours of observation.

As part of the transition of ocean color mapping, MODIS SST imagery processing could be adapted for a useable product to supplement or replace AVHRR or GOES data. MODIS SST data provides 1-km (Level 2) and 4.6-km, 36-km, and 1° (Level 3) resolutions over the global ocean. Every pixel has a quality-index parameter. The daily Level 2 product represents global day and night coverages every 24 hours; these coverages are used to produce the Level 3 product daily, 8-day weekly, monthly, and yearly for day and night conditions. Each data set has a quality index parameter. In terms of future missions, the VIIRS sensor onboard NPOESS will possess thermal capability and will provide the thermal image data required for HABMapS use.

The Geostationary Operational Environmental Satellite, or GOES-R, to be launched in 2012, will provide critical atmospheric, oceanic, climatic, solar and space data. The satellite will house an advanced imager, hyperspectral suite (including atmospheric sounding and coastal waters capabilities), lightning mapper, solar imager and space environment monitor.

3.1.3 Sea Surface Salinity

Salinity measured from orbit would be an important data stream for HAB researchers and operational forecasts. Changes in salinity strongly affect the persistence of a HAB. Ocean color scientists have developed an empirical methodology, using a three-channel visible/near-infrared algorithm, to estimate ocean salinity. However, the use of microwave radiometers will lead to more accurate salinity mapping.

Aquarius, a NASA mission planned for 2008, intends to produce global salinity maps (± 0.2 psu) on a monthly basis and to chart seasonal and year-to-year variations of sea surface salinity (SSS). The passive/active L- and S-band system (PALS) will include a set of three radiometers that are sensitive to salinity (1.413 GHz; L-band) and a scatterometer that corrects for ocean surface roughness.

3.1.4 Ocean Wind Fields

NOAA CoastWatch provides near real-time ocean-surface wind products with data from the QuikSCAT satellite and the NOAA/NASA Pathfinder Program Special Sensor Microwave/Imager (SSM/I). Although

the resultant wind products from each sensor are similar, each product has unique characteristics dependent on sensor performance and wind derivation methods. The QuikSCAT products use color as well as wind-barb notation to depict wind velocity (speed and direction), while the SSM/I products show only wind speed.

The SeaWinds scatterometer on NASA QuikSCAT provides global coverage of oceanic wind fields at 9-km resolution. NOAA/NCCOS currently uses these data as input to HAB trajectory analyses. NASA's AMSR-E sensor onboard Aqua also measures ocean wind fields and could be an additional data source for HAB tracking efforts. The planned NASA Ocean Vector Winds Mission (scheduled launch in 2008) will be a follow-on to SeaWinds.

3.1.5 Ocean Topography

The relief exhibited by the sea surface is due to both the relatively stable gravitational field of the Earth and the varying oceanic currents and wave fields that compose the sea surface. The normal oceanic state of sea-surface height (SSH) varies because of warming/cooling and seasonal wind vectors. NASA's TOPEX/Poseidon and Jason-1 sensors measure SSH to an accuracy of 4-5 cm. These SSH data are used to calculate the heat storage potential of the ocean and can be related to broad oceanic circulation patterns. NOAA NCCOS uses the ocean circulation patterns predicted from ocean topographic sensors to follow HAB movement. Scheduled for launch in December 2006, the Jason-2 Ocean Surface Topography Mission (OSTM) will be the follow-on to Jason-1's Poseidon-2 for supplying SSH data.

3.1.6 Ocean Circulation

Knowledge of oceanic circulation is critical for determining HAB movements. Ocean currents and frontal boundaries can be mapped by synthetic aperture radar (SAR), which detects ocean surface roughness. Since SAR imagery can delineate ocean features that could potentially concentrate and transport phytoplankton aggregations, these data can aid in the mapping of bloom transport. Clouds do not affect the collection of radar imagery. However, obtaining SAR data is expensive and the processed data might not be able to meet time constraints. Another issue is the impact of ocean wind fields on the acquired dataset – ocean wind fields can obscure relevant surface features.

3.1.7 Precipitation

Because *K. brevis*, for example, does not tolerate low salinity conditions, the amount of precipitation in coastal regions is a valuable data source for HAB forecasting. Precipitation rates from AMSR-E on Aqua and the Tropical Rainfall Measuring Mission (TRMM) could be an ancillary data source for HAB scientists. The precipitation radar on TRMM provides three-dimensional maps of storm structure. These maps give important information on storm depth, the height at which snow melts into rain, and the intensity and distribution of detected rain. TRMM also hosts the TRMM Microwave Imager (TMI), the workhorse of the TRMM measurement suite. TMI is a passive microwave sensor designed to provide quantitative rainfall information for the scene viewed by the TRMM satellite. Given the microwave energy emitted by the Earth and its atmosphere, TMI can map the water vapor, the cloud water, and the rainfall intensity in the atmosphere.

3.2 Possible Modeling-Related Contributions

The NASA REASoN project "Sensor to User - Applying NASA/EOS Data to Coastal Zone Management Applications Developed from Integrated Analyses" is a collaborative effort between Applied Coherent

Technology, Inc. (ACT) and NRL at Stennis Space Center. The project scope is to integrate real-time ocean measurements from NASA and NOAA satellites with coastal ocean model output into an automated, real-time database of ocean weather in the Gulf of Mexico.

The Naval Research Laboratory (NRL) has developed the Navy Coastal Ocean Model (Martin, 2000) and is working with the research community to develop the Hybrid Coordinate Ocean Model (HYCOM) model. NCOM is forced with auxiliary wind field and surface flux fields as well as assimilated sea surface height fields from altimetry data. NRL is developing and testing techniques for model nesting to provide high-resolution (~100 m) ocean products. In addition, NRL is developing methods to assimilate auxiliary data, such as satellite-derived observations, into the models to provide an improved capability. Databases will be generated each day for the model outputs. NRL plans to create over 900 ocean properties per day and place these in a 30-day revolving archive accessible to NOAA HAB forecasters.

This REASoN effort will focus on monitoring coastal ocean properties and provide new real-time support to NOAA HAB efforts. With significant NOAA collaboration, the parties involved in this REASoN project will extend the capabilities of ACT's patented software (WIPE) to automate NOAA's HAB Bulletin. The new application will serve MODIS, *in situ* data, and ocean model predictions; will automatically subset the data; and will create outputs in NOAA formats. Additionally, hybrid products from integrated analyses developed by NRL will reside in the new application. The new application will allow the analyst to concentrate on data interpretation and will provide a higher quality output to the end user. The user will be able to choose from a menu of output formats.

NOAA has expressed an interest in using Navy models for acquiring near real-time, three-dimensional profiles of Gulf of Mexico ocean properties (Stumpf, personal communication). The profiles can measure various ocean parameters such as the mixed layer depth, spectral light absorption of the water, irradiance attenuation with depth, salinity gradients, temperature profiles, and the variation of phytoplankton population density with depth. Currently, NOAA is using moored buoy instrumentation to provide profile data not accessible by remote sensors on orbital and sub-orbital platforms. Such moorings provide time-series data that are critical to understanding the evolution of HABs and needed for prediction of HAB trajectories. However, buoys only provide point data, not synoptic data.

3.2.1 Hydrodynamic Circulation Models

The models that are most applicable to HAB monitoring and forecasting are the Princeton Ocean Model (POM), the Navy Coastal Ocean Model (NCOM), SHOREline CIRCulation model (SHORECIRC), ADvanced CIRCulation model (ADCIRC), a variant on the S-Coordinate Rutgers University Model (SCRUM) called the Regional Ocean Model System (ROMS), and the General NOAA Oil Modeling Environment (GNOME). Generally, these physical models require input of meteorological conditions, coastline vector files, relevant bathymetry, and other estimated parameters such as bottom friction. Model computation time is dependent upon grid size and resolution, parallel or serial software code implementation, and basic hardware capability.

NCOM is a spatially 3-D time-independent numerical physical ocean model based on the primitive equations of motion. The model predicts temperature, salinity, and 3-D velocity fields. The model also takes into account both bathymetry and coastline geometry. NRL uses NCOM to produce real-time nowcasts at 1/8-degree resolution for the global ocean. NCOM is a spatially 3-D time independent numerical physical ocean model based on the primitive equations of motion. NCOM predicts temperature, salinity, and 3-D velocity fields and considers both bathymetry and coastline geometry in its predictions.

NOAA's Monitoring and Event Response for Harmful Algal Blooms (MERHAB) and the ECOHAB have funded development of 3-D hydrodynamic models for the eastern Gulf of Mexico (Stumpf, 2004). The University of South Florida (USF) has developed a numerical model based on the POM for the entire West Florida Shelf. The model has been successful in simulating past ocean events and will be coupled to the COMPS real-time buoy data stream to be run in a nowcast/forecast mode. USF routinely collects AVHRR SST and SeaWiFS and MODIS ocean color data in the West Florida Shelf area and integrates it with *in situ* data and model output to provide a comprehensive analysis of eastern GOM conditions.

SHORECIRC is a depth-integrated, short wave-averaged model solved using finite-difference methods (Putrevu and Svendsen, 1992; Svendsen and Putrevu, 1994). SHORECIRC is a quasi-3D model that includes the effect of current structure over depth. SHORECIRC could provide a full 3-D depiction of nearshore circulation within the Gulf of Mexico coast for HAB applications.

ADCIRC² is a collection of computer programs for solving time-dependent, free-surface circulation and transport problems in two or three dimensions. These programs use a spatial finite element approach and run on highly flexible irregularly spaced grids. Typical ADCIRC applications include modeling tidally and wind-driven circulation in coastal waters, forecasting hurricane storm surge and flooding, feasibility studies of dredging and material disposal, and performing larval transport studies.

GNOME is a free computer program used during oil spills within aquatic environments. The model provides predicted oil trajectories and uncertainty analyses for its forecasts. The model also predicts how types of spilled oil change chemically and physically during their residence times. The required input data include currents, winds, tides, and location files. NOAA is developing location files that include a base map, current patterns, and relevant climatology and tidal information; the majority of these location files are for coastal areas. NOAA scientists have shown that *K. brevis* longshore transport can be hindcast accurately using GNOME. When the HAB Bulletin becomes operational in September 2004 (it is now a prototype), GNOME will be used to perform trajectory modeling of HAB events within the Gulf of Mexico and will run twice a week to provide input to the HAB Bulletin.

Biophysical modeling, i.e., hydrodynamic modeling coupled with HAB biological components such as lifecycle, would be the most useful to HAB forecasting. Currently, NOAA HAB forecasting efforts employ several models, satellite imagery, and in-situ data (Stumpf, 2004). This is not an automated procedure and requires experienced scientists to make assessments and predictions based on available data.

3.2.2 Sea Surface Temperature Modeling

The NASA National Season-to-Interannual Prediction Project (NSIPP) is a coupled ocean-land-atmospheric model that provides an assimilation and forecast system capable of using a combination of satellite (SST) and *in situ* data to provide predictions of the El Niño – Southern Oscillation and of other major seasonal-to-interannual events and their relationships. NSIPP's Global Circulation Model uses the Goddard Earth Modeling System (GEMS) to couple atmospheric, ocean, and land models. The ocean's latitude-longitude grid defines the land-ocean mask for the coupled model; thus, each grid box comprises either entirely ocean or entirely land. The atmosphere-to-ocean couplers interpolate from the atmospheric grid to the mass point of the underlying ocean boxes, assuming the ocean grid boxes do not overlap atmospheric grid boxes. For atmosphere/ocean coupling, the interpolation consists of replicating

² ADCIRC was developed by Dr. Rick Luettich and by Dr. Joannes Westerink.

atmospheric values for each underlying ocean grid box. In ocean/atmosphere coupling, interpolation consists of averaging the underlying ocean grid boxes. The ocean model controls the evolution of the open-ocean, shallow seas, and sea ice. The atmosphere treats inland lakes as land surfaces. NSIPP long-range predictions might be a potential candidate for HAB trajectory mapping and forecasting in the Gulf of Mexico.

3.2.3 HAB/HAB-Hydrodynamic Coupled Models

Recently, a bio-optical model was coupled to the NCOM at $\frac{1}{8}^\circ$ resolution as a follow-on to the Coupled Bio-physical-dynamics Across the Littoral Transition (CoBALT) advanced research initiative³. Ultimately, the concept of coupling a realistic HAB ecological model to a hydrodynamic model serves as a lodestar of HAB-related research. Initial attempts at bio-optical couplings to models such as NCOM presage such a development. CoBALT might be made useable to NOAA via the NASA REASoN project.

Similarly, Lorenzo et al. (2004) recently coupled ROMS to a 3-D ecosystem model to study the California Current System. The ecosystem model is a seven-component model involving nutrient concentrations, phytoplankton, zooplankton, and detritus. The biological components are coupled with an advection-diffusion equation and non-linear source-sink coupling terms. The ROMS improves upon the capability of SCRUM in that it possesses improved physics and a parallel architecture. This model uses generalized sigma-coordinates in the vertical and a curvilinear horizontal grid to model coastal areas. NASA Jet Propulsion Laboratory has used this model to study the Southern California Bight. QuikSCAT wind vectors were coupled with the to assess air-sea interactions. The successful application of ROMS to several coastal environments makes ROMS a potential candidate for adaptation and use in HAB modeling efforts.

3.2.4 Summary of NASA Potential Contributions

The most immediately useful NASA contributions appear to be the 1-km MODIS chlorophyll and SST products and the (presently used) SeaWinds wind vector data. MODIS pigment concentration and SST data are sufficiently mature to replace SeaWiFS and AVHRR imagery used in NOAA HAB applications. The large file size of MODIS data is an impediment to NOAA use and modified processing schemes would aid in NOAA's adoption of these products for operational HAB forecasting (Stumpf, personal communication).

GNOME is the ocean circulation model that NOAA intends to use when the HAB Bulletin becomes operational. However, NCOM combines more sophisticated physics and is coupled to bio-optical models of coastal waters. Another candidate model for NOAA use is the ROMS, which has been coupled to a seven-component ecosystem model for NASA-JPL applications. This linked model could possibly be adapted to serve as an incipient approach for coupling HAB ecology to ocean dynamics.

4.0 Conclusions and Recommendations

HABMapS and the HAB Bulletin provide a Web-based GIS and an e-mail alert system that allow the detection, monitoring, and tracking of HAB events in the Gulf of Mexico. HABMapS comprises GIS data layers developed by the overarching HABSOS effort. The key inputs to HABMapS are cell counts, buoy and satellite winds, atmospheric model forecasts, surface currents, SST, bathymetry, county maps, major

³ This coupled model has been developed by researchers Paul Martin and Allan Wallcraft at NRL.

rivers, cities, shellfish beds, and marine and estuarine reserves. The HAB Bulletin alerts users of a HAB in the Gulf of Mexico, and HABMapS begins to monitor, map, and forecast the trajectory and dynamics of the bloom. Presently, the relative effectiveness of the HABSOS/HABMapS DST is on par with hurricane forecasting (Stumpf, 2004).

The most straightforward NASA contribution to NOAA HAB forecasting efforts is ocean color imagery. Because SeaWiFS is an aging sensor, MODIS would provide continuity of ocean color (and SST) products for the HAB Bulletin. MODIS provides spectral channels similar to SeaWiFS for spectral assessment of scene contents, although MODIS ocean color algorithms for coastal waters may need continued refinement to enable accurate chlorophyll retrievals.

Other relevant areas where NASA contributions could be important are atmospheric/ocean circulation modeling and their coupling (NSIPP), as well as sea surface height data (Jason). NOAA HAB models rely on accurate hydrodynamic and meteorological information model input for prediction of HAB location and trajectory (especially when clouds obscure satellite imagery) and what the bloom population dynamics might be at that specific place and time. Enhanced model development is the single most important development area that could aid NOAA HAB forecasting (Stumpf, personal communication). The baseline model performance is the present non-automated, heuristic approach with several model outputs used by NOAA scientists to make intelligent determinations for HAB forecasting. With more accurate model development, computer simulations could improve forecasts with less cost and time expenditure.

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Appendix A. Glossary

Benchmark – A standard by which a product can be measured or judged (i.e., How did the DST that assimilated NASA measurements compare in its operation, function, and performance to the earlier version). The benchmarking process is required to support adoption of innovative solutions into operational environments that affect life and property.

Decision Support Tools (DSTs) – a suite of solutions owned by NASA partners that are used in a variety of problem domains for decision and policymaking. These solutions could include assessments, decision support systems, decision support calendars, etc.

Evaluation – Identify decision support tools (assessments and DSTs) that have been developed by Federal agencies and other partners that are a priority to citizens of our nation and that can be enhanced by NASA ESE results. Develop the specifications for how the candidate DST can be augmented by assimilating NASA ESE observations and predictions.

Validation – A process to ensure the completed products (software, algorithm, model) effectively serve the functional requirements.

Verification – A life cycle process to ensure the products being developed meet the stated specifications (functional, performance, and design).

Appendix B. Abbreviations and Acronyms

ACT	Applied Coherent Technology, Inc.
ADCIRC	Advanced Circulation (model)
AVHRR	Advanced Very High Resolution Radiometer
CDOM	Colored Dissolved Organic Matter
CHRIS	Compact High Resolution Imaging Spectrometer
CoBALT	Coupled Bio-physical-dynamics Across the Littoral Transition
COMPS	Coastal Ocean Monitoring and Prediction System
CSC	Coastal Services Center
CZCS	Coastal Zone Color Scanner
DST	Decision Support Tool
ECOHAB	Ecology and Oceanography of Harmful Algal Blooms
Envisat	Environment Satellite
ESA	European Space Agency
ESE	Earth Science Enterprise
GAC	Global Area Coverage
GEMS	Goddard Earth Modeling System
GFDL	Geophysical Fluid Dynamics Laboratory
GIS	Geographic Information System
GLI	Global Imager
GOES	Geostationary Operational Environment Satellites
GOM	Gulf of Mexico
GSFC	Goddard Space Flight Center

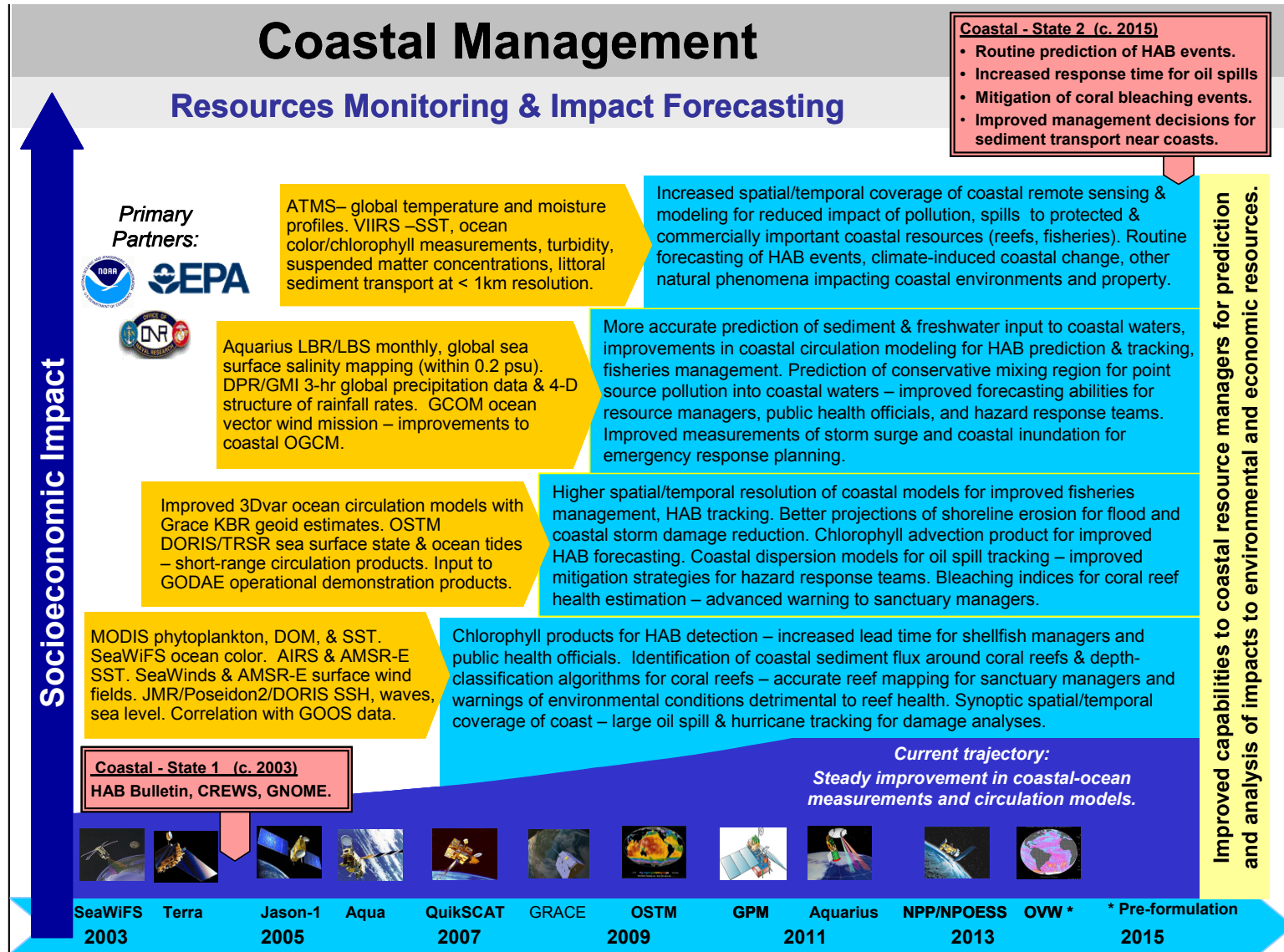
HAB	Harmful Algal Bloom
HABMapS	Harmful Algal Bloom Mapping System
HABSOS	Harmful Algal Blooms Observing System
HSI	Hyperspectral Sensor Imager
HyCODE	Hyperspectral Coupled Ocean Dynamics Experiment
JAXA	Japan Aerospace Exploration Agency
LAC	Local Area Coverage
LIF	Laser Induced Fluorescence
MERIS	Medium Resolution Imaging Spectrometer
MIT	Massachusetts Institute of Technology
MODIS	Moderate Resolution Imaging Spectroradiometer
MOM	Modular Ocean Model
NASDA	National Space Development Agency of Japan (through 9/30/2003; now JAXA)
NCCOS	National Centers for Coastal Ocean Science
NCOM	Navy Coastal Ocean Model
NDBC	National Data Buoy Center
NIR	Near Infrared
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service (NOAA)
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRL	Naval Research Laboratory
NSIPP	National Season-to-Interannual Prediction Project

ORBIMAGE	Orbital Imaging Corporation
OSCR	Ocean Surface Current Radar
OSE	Ocean State Estimation
PAR	Photosynthetically Available Radiation
POM	Princeton Ocean Model
PORTS®	Physical Oceanographic Real-Time System
PROBA	Project for On Board Autonomy
QuikSCAT	Quick Scatterometer
REASoN	Research, Education, and Applications Solutions Network
ROMS	Regional Ocean Model System
SAR	Synthetic Aperture Radar
SCRUM	S-Coordinate Rutgers University Model
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SHORECIRC	Shoreline Circulation (model)
SLFMR	Scanning Low-Frequency Microwave Radiometer
SMOS	Soil Moisture – Ocean Salinity
SNR	Signal to Noise Ratio
SPM	Suspended Particulate Matter
SSC	Stennis Space Center
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
STARRS	Salinity Temperature and Roughness Remote Scanner
TABS	Texas Automated Buoy System

Evaluation of the Harmful Algal Bloom Mapping System (HABMapS) and Bulletin

TMI	TRMM Microwave Imager
TRMM	Tropical Rainfall Measuring Mission
VIIRS	Visible/Infrared Imager/Radiometer Suite
WIPE	WWW Information Processing Environment

Appendix C. Applications Roadmap: Coastal Management



Appendix D. Relevant Earth Observing Missions and Sensors

Table D-1. List of sensors and missions mentioned in this report.

Sensor	AMSR AVHRR SeaWiFS MODIS TMI VIIRS Hyperion AOL SeaWinds
Mission	Aqua Aquarius GOES NPOESS Jason-1/2 TRMM Terra POES EO-1 SMOS QuikSCAT

D.1. MODIS

MODIS

(Moderate Resolution Imaging Spectroradiometer)



MODIS on Terra and Aqua comprehensively measure ocean, land, and atmospheric processes over the entire Earth every 1 to 2 days from complementary orbits, acquiring data in 36 spectral bands and 3 different spatial resolutions. These data will improve our understanding of global Earth system dynamics and the interactions between land, ocean, and lower atmosphere processes.

MISSIONS:

- [Terra](#) – Dec. 1999
- [Aqua](#) – May 2002

HERITAGE:

- [AVHRR](#)
- [High Resolution Infrared Radiation Sounder \(HIRS\)](#)
- [Landsat TM](#)
- [CZCS](#)

LINKS:

- Sensor Site:
<http://modis.gsfc.nasa.gov/>
- Data Sites:
<http://daac.gsfc.nasa.gov/>
<http://edcdaac.usgs.gov/main.html>

PRODUCT SUMMARY:

- High-priority global dynamics and processes occurring on the land, in the oceans, and in the lower atmosphere; surface temperatures of land and ocean, chlorophyll fluorescence, land cover measurements, cloud cover

VITAL FACTS:

- Instrument: Whiskbroom imaging radiometer
- Bands: 36 from 0.4 and 14.5 μm
- Spatial Resolution: 250 m, 500 m, and 1,000 m
- Swath: 2,330 km (across track) by 10 km (along track at nadir)
- Repeat Time: Global coverage in 1-2 days
- Design Life: 6 years

OWNER:

- U.S., NASA

FOLLOW-ON:

- VIIRS – NPOESS



D.2. SeaWinds

SeaWinds



The SeaWinds instrument is a specialized microwave radar that measures near-surface wind speed and direction under all weather and cloud conditions over Earth's oceans.

MISSIONS:

- [QuikSCAT](#) – June 1999
- [ADEOS II](#) (Midori II)– Dec. 2002

HERITAGE:

- SeaSat
- [NSCAT](#)

LINKS:

- Sensor Site:
<http://winds.jpl.nasa.gov>
- Data Site:
<http://podaac.jpl.nasa.gov>

PRODUCTS SUMMARY:

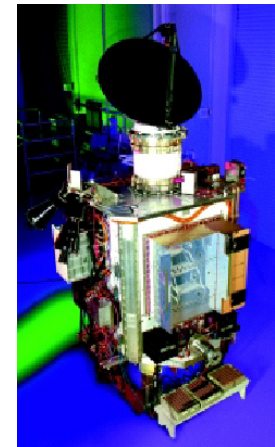
- Sea surface wind speed and direction

VITAL FACTS:

- Instrument: conical scanning scatterometer
- Frequency: Microwave; 13.4 GHz
- Spatial resolution: 25 km
- Swath: 1,600 km
- Repeat Time: 4 days
- Design Life: 3 years

OWNERS:

- U.S., NASA
- Japan, NASDA



D.3. Jason-1

JASON-1



Jason-1 is a joint mission between France and the U.S. to monitor global ocean circulation, to improve global climate predictions, and to monitor events such as El Niño Southern Oscillation conditions and ocean eddies.

MISSION SENSORS:

- DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) receiver
- JMR (Jason Microwave Radiometer)
- LRA (Laser Retroreflector Array)
- Poseidon-2 SSALT-2 (Solid State radar ALTimeter)
- TRSR-GPS Receiver

VITAL FACTS:

- Orbit Type: Non Sun-Synchronous
- Altitude: 1,336 km
- Inclination: 66°
- Launch Date: December 7, 2001
- Design Life: 3 years

OWNERS:

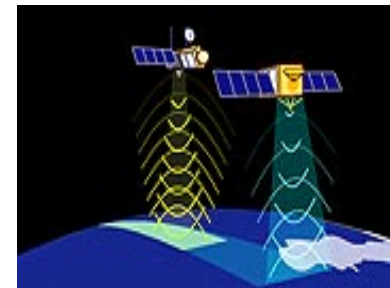
- U.S., NASA
- France, CNES

MEASUREMENTS:

- Brightness temperature
- Water vapor content
- Liquid water content
- Ocean topography and circulation

LINKS:

- <http://sealevel.jpl.nasa.gov>
- <http://topex-www.jpl.nasa.gov/mission/jason-1.html>



D.4. VIIRS (Planned)

VIIRS

(Visible Infrared Imaging Radiometer Suite)



MISSIONS:

- [NPP](#) – 2006
- [NPOESS](#) – 2010

HERITAGE:

- [MODIS](#)
- AVHRR
- DMSP – Operational Linescan System (OLS)
- [SeaWiFS](#)

LINK:

- Sensor Site:
http://www.ipo.noaa.gov/Technology/viirs_summary.html

VIIRS will collect visible/IR imagery and radiometric data. Data types will include atmospheric, clouds, Earth radiation budget, clear-air land/water surfaces, sea surface temperature, ocean color, and low light visible imagery. It will combine the radiometric accuracy of the AVHRR with the higher (0.65 km) spatial resolution of the Operational Linescan System flown on DMSP.

PRODUCT SUMMARY:

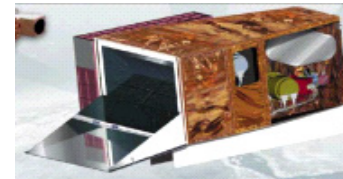
- Data types such as atmospheric, clouds, Earth radiation budget, clear-air land/water surfaces, sea surface temperature, ocean color, and low light visible imagery

VITAL FACTS:

- Instrument: Whiskbroom imaging radiometer
- Bands: 22 between 0.3 μm -14 μm
- Spatial Resolution: ~400 m (nadir)
- Swath: ~3,000 km
- Repeat Time: 1 day
- Design Life: 7 years

OWNERS:

- U.S., NOAA
- U.S., NASA



D.5. NPOESS (Planned)

NPOESS

(National Polar-orbiting Operational Environmental Satellite System)



NPOESS will provide the U.S. with an enduring capability to measure atmospheric, land, and oceanic environmental parameters globally. The system will provide timely and accurate weather and environmental data to weather forecasters, military commanders, civilian leaders, and the scientific community. The current plan is for the NPOESS constellation to consist of three polar-orbiting satellites.

MISSION SENSORS:

- VIIRS (Visible/Infrared Imager/Radiometer Suite)
- CMIS (Conical Microwave Imager/Sounder)
- CrIS (Crosstrack Infrared Sounder)
- GPSOS (Global Positioning System Occultation Sensor)
- OMPS (Ozone Mapping and Profiler Suite)
- SESS (Space Environment Sensor Suite)
- TIM (Total Irradiance Monitor)
- SIM (Spectral Irradiance Monitor)

LINKS:

- <http://www.ipo.noaa.gov/index2.html>

VITAL FACTS:

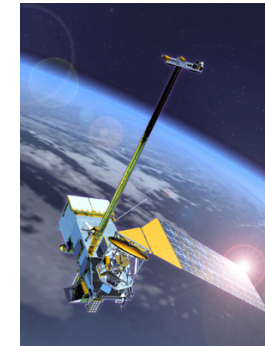
- Orbit Type: Sun-Synchronous
- Altitude: 833 km
- Inclination: 98.75°
- Launch Date: September 1, 2010
- Design Life: 5 years

MEASUREMENTS:

- Atmospheric temperature, water vapor profiles, and auroral boundary traits
- Electron density and ionospheric profiles
- Ozone distribution
- Total solar irradiance and solar spectral irradiance
- Earth radiation budget, land/water and sea surface temperature, ocean color, and low light imagery

OWNERS:

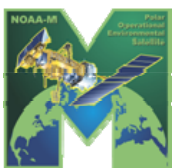
- U.S., NASA
- U.S., NOAA



D.6. AVHRR/3

AVHRR/3

(Advanced Very High Resolution Radiometer 3)



The AVHRR/3 is a six channel imaging radiometer which detects energy in the visible and IR portions of the electromagnetic spectrum. The instrument monitors reflected energy in the visible and NIR portions of the electromagnetic spectrum to observe vegetation, clouds, lakes, shorelines, snow, aerosols, and ice.

MISSIONS:

- **POES** – May 1998, Sept. 2000, June 2002

HERITAGE:

- AVHRR/2
- AVHRR

LINKS:

- Sensor Site:
<http://www2.ncdc.noaa.gov/docs/km/index.htm>
- Data Site:
<http://www.ssa.noaa.gov/8080/cocoon/ssa/>

PRODUCT SUMMARY:

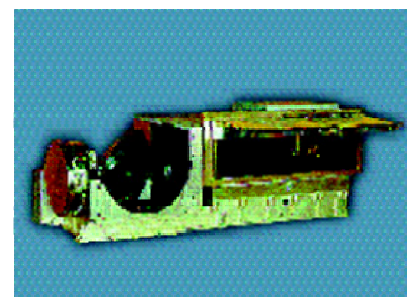
- Measurements of reflected solar (visible and near-IR) energy and radiated thermal energy from land, sea, clouds, and the intervening atmosphere

VITAL FACTS:

- Instrument: across track scanning radiometer
- Bands: Six from 0.58 and 12.5 μm
- Spatial Resolution: 0.5 km (VIS), 1km (IR)
- Swath: 2,940 km
- Repeat Time: 1 day
- Design Life: 3 to 5 years

OWNER:

- U.S., NOAA



D.7. SeaWiFS

SeaWiFS

(Sea-viewing Wide Field-of-view Sensor)



The purpose of SeaWiFS data is to examine oceanic factors that affect global change and to assess the oceans' role in the global carbon cycle, as well as other biogeochemical cycles. SeaWiFS data will be used to help clarify the magnitude and variability of chlorophyll and primary production by marine phytoplankton, and to determine the distribution and timing of spring algal blooms.

MISSION:

- [SeaWiFS](#) – Aug. 1997

PRODUCT SUMMARY:

- Observations characterizing the dynamics of ocean and coastal currents, the physics of water mass mixing, and ocean color and biology

OWNERS:

- U.S., NASA
- U.S., ORBIMAGE

HERITAGE:

- [Coastal Zone Color Scanner \(CZCS\)](#)

VITAL FACTS:

- Instrument: Whiskbroom imaging radiometer
- Bands: Eight between 0.4-0.9 μm
- Spatial Resolution: 1.1 km and 4.5 km
- Swath: 2,800 km and 1,500 km
- Repeat Time: 1-2 days
- Design Life: 5 years

LINKS:

- Sensor Site:
<http://seawifs.gsfc.nasa.gov/SEAWIFS.html>
- Data Site:
<http://seawifs.gsfc.nasa.gov/SEAWIFS/IMAGES/IMAGES.html>



D.8. QuikSCAT

QuikSCAT (Quick Scatterometer)

QuikSCAT, a "quick recovery" mission to fill the gap created by the loss of data from NSCAT, is benchmarked with the National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite, Data, and Information Service (NESDIS) Office of Research and Applications. QuikSCAT is currently intended to record sea-surface wind speed and direction data for global climate research and operational weather forecasting and storm warning.

MISSION SENSOR:

- SeaWinds

VITAL FACTS:

- Orbit Type: Sun-Synchronous
- Altitude: 803 km
- Inclination: 98.6°
- Launch Date: June 18, 1999
- Design Life: 2 years

OWNER:

- U.S., NASA

MEASUREMENTS:

- Sea surface wind velocity and wind direction
- Sea ice distribution

LINK:

- <http://winds.jpl.nasa.gov/missions/quikscat/quikindex.html>



D.9. Aquarius

Aquarius



Aquarius will measure global Sea Surface Salinity (SSS). Scientific progress is limited because conventional *in situ* SSS sampling is too sparse to give the global view of salinity variability that only a satellite can provide. Aquarius will resolve missing physical processes that link the water cycle, the climate, and the ocean.

MISSION:

- **ESSEP-3 – 2007**

PRODUCT SUMMARY:

- **Observation for modeling the processes that relate salinity variations to climatic changes in the global cycling of water and to understand how these variations influence general ocean circulation**

OWNER:

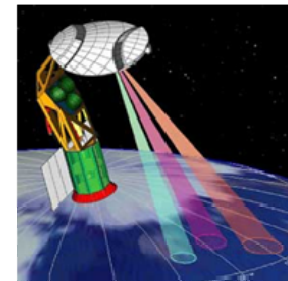
- **U.S., NASA**

VITAL FACTS:

- **Instruments:** Radiometer/scatterometer
- **Frequencies:** 1.413 GHz, 1.26 GHz
- **Spatial Resolution (footprint):** 62 km x 68 km, 68 km x 62 km, 75 km x 100 km
- **Swath:** 300 km
- **Repeat Time:** 8 days
- **Design Life:** 3 years

LINK:

- **Sensor Site:**
<http://esep.gsfc.nasa.gov/aquarius/>



D.10. AMSR

AMSR (Advanced Microwave Scanning Radiometer)



AMSR is a passive microwave radiometer. It observes atmospheric, land, oceanic, and cryospheric parameters, including precipitation, sea surface temperatures, ice concentrations, snow water equivalent, surface wetness, wind speed, atmospheric cloud water, and water vapor.

MISSION:

- Aqua – May 2002 (AMSR-E)
- [ADEOS II](#) – Dec. 2002 (AMSR)

HERITAGE:

- [MSR](#)
- SMMR
- SSM/I

LINKS:

- Sensor Sites:
<http://wwwghcc.msfc.nasa.gov/AMSR/>
http://sharaku.eorc.nasda.go.jp/AMSR/index_e.htm
<http://aqua.nasa.gov/AMSRE3.html>
- Data Site:
<http://nsidc.org/data/amslr/data.html>

PRODUCT SUMMARY:

- Atmospheric and weather monitoring

VITAL FACTS:

- Instrument: Passive microwave radiometer
- Bands: Six (AMSR-E) and eight (AMSR) from 6-89 GHz
- Spatial Resolution: from ~5 km at 89 GHz to ~50 km at 6 GHz
- Swath: 1,445 km (AMSR-E), 1,600 km (AMSR)
- Repeat Time: 4 days
- Design Life: 3 years

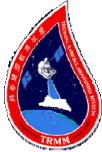
OWNER:

- Japan, NASDA
- U.S., NASA



D.11. TMI

TMI (TRMM Microwave Imager)



The Tropical Rainfall Measuring Mission's (TRMM) TMI is a passive microwave sensor designed to provide quantitative rainfall information over a wide swath under the TRMM satellite.

MISSION:

- [TRMM](#) – Nov. 1997

HERITAGE:

- DMSP-SSM/I

LINKS:

- Sensor Site: http://trmm.gsfc.nasa.gov/overview_dir/tmi.html
- Data Site: http://trmm.gsfc.nasa.gov/data_dir/data.html

PRODUCT SUMMARY:

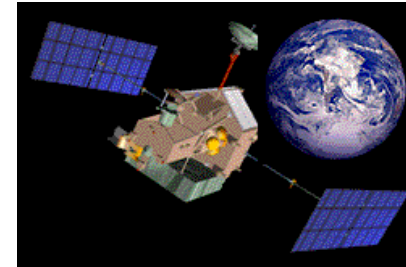
- Measures water vapor, cloud water, and rainfall intensity in the atmosphere

VITAL FACTS:

- Instrument: Across track scanning microwave radiometer
- Frequencies (five): Microwave; 10.7, 19.4, 21.3, 37, and 85.5 GHz
- Horizontal Resolution: Varies by frequency from 38.3-4.4 km
- Vertical Resolution: ~2.5 km
- Swath: 790 km
- Coverage: Global every 1-2 days
- Design Life: 6 years

OWNER:

- U.S., NASA



D.12. Hyperion

Hyperion



The Hyperion instrument provides a new class of Earth observation data for improved Earth surface characterization. Hyperion provides a science-grade instrument with precise calibration. The Hyperion resolves surface properties into 220 spectral bands.

MISSION:

- [EO-1](#) – Nov. 2000

PRODUCT SUMMARY:

- Hyperspectral imaging of land surfaces and land classification

OWNER:

- U.S., NASA

HERITAGE:

- LEWIS
Hyperspectral
Imaging
Instrument (HSI)

VITAL FACTS:

- Instrument: Hyperspectral pushbroom imager
- Bands: 220 bands 0.4 μm -2.5 μm
- Spectral resolution: .010 μm
- Spatial Resolution: 30 m
- Swath: 7.5 km
- Repeat Time: 16 days (8 days, selected regions)
- Design Life: 2 years

LINKS:

- Sensor Site:
<http://eo1.gsfc.nasa.gov/Technology/Hyperion.html>
- Data Site:
<http://eo1.usgs.gov/dataproducts/productdesc.asp>



D.13. SMOS

SMOS

(Soil Moisture and Ocean Salinity)



The Soil Moisture and Ocean Salinity (SMOS) mission is the second Earth Explorer Opportunity mission scheduled for launch in 2006. Its overall objectives are to provide global observations of two crucial variables for modeling the weather and climate: soil moisture and ocean salinity. The SMOS mission will also monitor vegetation water content, snow cover, and ice structure.

MISSION SENSORS:

- MIRAS (Microwave Imaging Radiometer using Aperture Synthesis)—passive L-band 2D-interferometer

VITAL FACTS:

- Orbit Type: Sun-Synchronous
- Altitude: 755 km
- Launch Date: January 2006
- Design Life: 3 years

OWNER:

- Europe, ESA

MEASUREMENTS:

- Sea surface salinity and soil moisture in support of climate, meteorology, hydrology, and oceanography applications

LINKS:

- <http://www.esa.int/export/esaLP/smos.html>



D.14. Terra

Terra



The Terra satellite provides global data on the state of the atmosphere, land, and oceans, as well as their interactions with solar radiation and with one another. Japan, Canada, and the U.S. have provided instruments for this mission.

MISSION SENSORS:

- ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer)
- CERES (Clouds and the Earth's Radiant Energy System)
- MISR (Multi-angle Imaging Spectro-Radiometer)
- MODIS (Moderate Resolution Imaging Spectroradiometer)
- MOPITT (Measurements of Pollution in the Troposphere)

LINKS:

- <http://terra.nasa.gov>

VITAL FACTS:

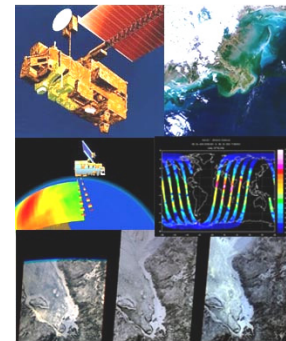
- Orbit Type: Sun-Synchronous
- Altitude: 705 km
- Inclination: 98.2°
- Launch Date: December 18, 1999
- Design Life: 6 years

MEASUREMENTS:

- Surface bi-directional reflectance distribution function
- Carbon monoxide and methane in the troposphere
- High-resolution images and maps of land surface temperature
- Earth's radiation budget and atmospheric radiation
- Sea surface temperature and ocean productivity

OWNER:

- U.S., NASA
- U.S., JPL



D.15. EO-1

NMP EO-1 (New Millennium Program Earth Observing-1)



EO-1 is designed to demonstrate and validate advanced instruments, spacecraft systems, and mission concepts in flight. It has returned scientific data as a by-product of its testing to support land cover change and atmospheric constituents.

MISSION SENSORS:

- ALI (Advanced Land Imager)
- Hyperion – Hyperspectral Imager
- LAC (Linear Etalon Imaging Spectrometer (LEISA) Atmospheric Corrector)

LINKS:

- <http://eo1.gsfc.nasa.gov>

VITAL FACTS:

- Orbit Type: Sun-Synchronous
- Altitude: 705 km
- Inclination: 98.2°
- Launch Date: November 21, 2000
- Design Life: 2 years

MEASUREMENTS:

- Land cover and land use change
- Hyperspectral Visible–Short-wave infrared
- Vegetation dynamics
- Water vapor profile for atmospheric correction

OWNER:

- U.S., NASA



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